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RESEARCH

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Optimal design and analysis of wireless power transfer system with converter circuit

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Abstract

Wireless power transfer (WPT) technology has many applications by virtue of its intrinsic safety and convenience characteristics. This is particularly so when the WPT systems are used in conjunction with implanted medical devices, as they can greatly reduce the pain of patients and their financial burdens. In previous researches, the optimal system mainly focuses on the design of the coils which includes the transmitter coil and the receiver coil. In this paper, the WPT system will be optimized to include also the power source circuit and the load circuit, in addition to the coils, as an integral system. A simple circuit which converts the DC source into AC excitation as the feeding circuit is included in the WPT system. In this convert circuit, there are two inductors which can be formed by coils. In the WPT system, the two coils in the convert circuit are transmitter coils. In addition, the receiver coil should be optimized. Thus, the WPT system is constructed by the three coils. In this paper, the parameters in the convert circuit are considered along with the coil parameters in the optimization study.

Keywords: Convert circuit, Finite element method, Optimization method, Power source circuit, Wireless power transfer

1 Introduction

Wireless power transfer (WPT) system has a great application potential, because of the development of the electronic devices. Comparing with the traditional method of power transfer using magnetic inductive coupling in achieving wireless and efficient near-field power transfer, there are increasing number of researchers that focus on the magnetic resonant coupling method [1–3].

Since 1960s, the implanted medical devices for various functions gradually have permeated into people's lives, such as pacemaker, deep brain stimulator, and nerve stimulator, which reduce the patients' pain and effectively prolong their life. Although the industry of the implanted medical devices is in a rapid development, it also faces some problems, such as the battery life. In order to guarantee the normal work of the implanted devices, patients must regularly detect the remaining capacity of the battery. A new battery must replace the exhausted battery through surgery which not only increase the patients' economic burden but also bring the patients' physical trauma.

To seek more efficient and durable power supply way, therefore, become one of the key technologies of the implanted medical devices. After entering the end of the twentieth century, to realize the wireless charging for implanted medical devices provides a safe and reliable method to solve the supply problem. Thus WPT technology receives more and more attentions from the researchers in biomedical engineering [4–7].

In 2007, the MIT research team proposed the "WiTricity" system using the magnetic resonant coupling [8, 9]. In the WPT system, it is composed of two coil systems, one is a transmitter coil which is connected to a source to generate a shifting magnetic field, and the other one is a receiver coil which keeps away from the transmitter coil without a wire. The excitation of the WPT system should be a sinusoidal function. In practice, the sinusoidal function is obtained by a convert circuit which connects to a DC source.

The receiver coil induced voltage through catching the magnetic fluxes generated by the transmitter coil. As shown in Fig. 1, the WPT system includes a DC power

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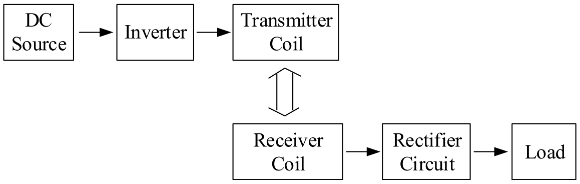


Fig. 1 Typical structure of WPT system

source, inverter, transmitter, receiver, rectifier circuit, and load. The inverter is applied to invert the DC source into a sinusoidal source to provide a shifting current in the transmitter coil. In the previous research, the works about the WPT system almost focus on the coil design when the system is optimized [10–12]. In the system, the inverter circuit is too complicated to be optimized along with the coil system.

Generally, power transfer efficiency is as the objective function under some constrains, such as the volume of the receiver coil or the power transfer distance. According to the application background, sometimes, the power transfer efficiency and the maximum power transfer are both as the objective functions [13]. Under this condition, the multi-objective optimization method [14, 15] can be used to design the WPT system. In this paper, the power transfer efficiency is chosen as the objective function. The WPT model is formulated as a constrained optimization problem. It is a simulation-based optimization problem with mixed discrete-continuous variables. Metaheuristic approaches are generally appropriate and hence commonly used for solving such optimization problems.

In this paper, a simple convert circuit is used to convert a DC source into an AC source. This circuit is applied into the WPT system for implanted medical devices. Thus, the system can be optimized and analyzed as a whole. A differential evolution (DE) algorithm is used to analyze the model. It is simple to implement, easy to use, and computationally fast.

2 Convert circuit as feeding circuit

In the WPT system, the DC source is converted into AC source using a convert circuit. In order to make the WPT system simple, the following circuit shown in Fig. 2 is as the feeding circuit to connect with the WPT system [16]. In this circuit, the basic components are DC power supply, resistor R_1, capacitors C_1, C_2, and C_3, inductors L_1 and L_2, together with a bipolar junction transistor (BJT) T.

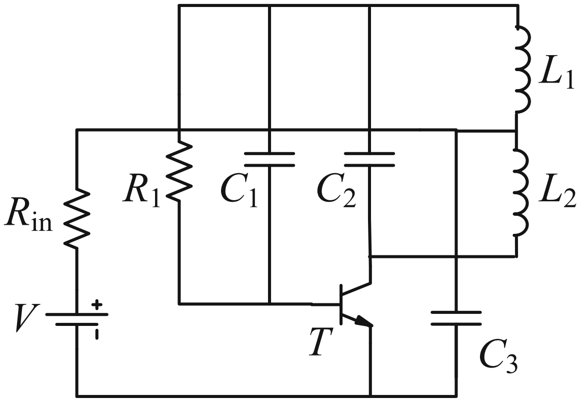


Fig. 2 The feeding circuit which converts DC into AC

In the circuit, R_1 is used to limit the amplitude of the current flowing into the BJT to guarantee its proper operation; the capacitors C_1 and C_3 are assist components to ensure that the circuit gives more stable output voltage and current; the characteristic of power switch of BJT is used to carry out the conversion from DC to AC. When the excitation in the feeding circuit is a DC voltage, the output voltage and current in L_2 are shown in Fig. 3a and b respectively. It can be seen that the output voltage and current are both a sinusoidal function.

The driving frequency of the feeding circuit is determined by the components L_1, L_2, and C_2. The frequency can be calculated by

$$f_0 = \frac{1}{2\pi\sqrt{(L_1 + L_2)C_2}}. \tag{1}$$

For testing, the convert circuit is analyzed firstly. The specifications of the circuit are listed in Table 1.

According to (1), the frequency of the convert circuit is 13.56 MHz after the values of inductance and capacitance are substituted. The voltage and current in L_2 are shown in Fig. 3. It can be seen that the output voltage in L_2 becomes a sinusoidal function with 5-V amplitude from the DC source. The sinusoidal current in L_2 can generate a shifting electromagnetic field which is a key medium in the WPT system.

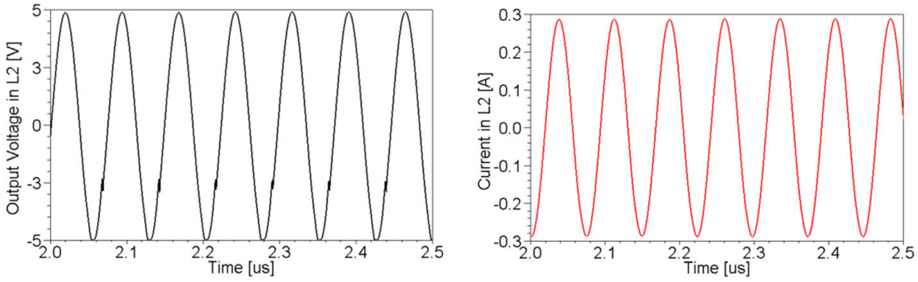
3 Analysis methods

3.1 Analysis procedure

In this paper, the WPT system applied in the implanted medical devices is optimized and designed. The analysis procedure is shown in Fig. 4. Firstly, the feeding circuit as shown in Fig. 2 is analyzed to find its optimal parameters and the relationship between the two inductances. The aim of the analysis is to obtain the maximum current in L_2. Then an optimization method is designed with the above results as the restrict conditions. As a whole, finally, the WPT system is optimized according to the determined initial parameters of the receiver coil.

3.2 Initial analysis

Before the WPT system is analyzed, the feeding circuit as shown in Fig. 2 is analyzed firstly. During analysis, the parameters in the feeding circuit will be analyzed while



a **b**

Fig. 3 The sinusoidal voltage and current in the inductance L_2

keeping the BJT to work in the amplifier region. The capacitors C_1 and C_3 are analyzed. Figure 5a presents the current in L_2 varied with C_1 and Fig. 5b presents the current in L2 varied with C_3.

It can be seen that, the output current in L_2 reaches the maximum value when C_1 is about 4 pF as shown in Fig. 5a. In Fig. 5b, it indicates that the value of C_3 has no effect on the output current in L_2. Its role is just to ensure that the BJT circuit has a relative high voltage gain.

In the feeding circuit, the parameter R_1 also impacts output current in L_2 as shown in Fig. 6. It can be seen that the output current in L_2 will reach the maximum value when R_1 is about 3 kOhm.

In order to find the relationship of the values of L_1 and L_2, the frequency of the feeding circuit is fixed. Then the output currents in L_2 are obtained by varying with the values of L_1 and L_2 as shown in Fig. 7. It can be seen that the output current will reach its maximum when the values of the two inductors are chosen correctly.

3.3 Optimization method

In this paper, a differential evolution (DE) algorithm is used to analyze the model. It is simple to implement, easy to use, and computationally fast. The DE algorithm includes the following two equations for producing the candidate solutions:

$$v_i = x_{r1} + F(x_{r2} - x_{r3}), \tag{2}$$

Table 1 Specifications of the convert circuit

Parameters	Values
V	5 V
L_1	0.1 μH
L_2	0.2 μH
R_1	5.1 kΩ
C_3	220 nF
C_1	1 nF
C_2	459 pF

$$u_{j,i} = \begin{cases} v_{j,i}\,, \ if \ \ r_4 \le Cr \quad \text{or} \quad j = k \\ x_{j,i}, \text{otherwise} \end{cases} \quad , j = 1, 2, \ldots, D. \tag{3}$$

where x_{r1}, x_{r2}, and x_{r3} are the solutions; v_i is called the mutant vector; and u_i is a candidate solution. Equations (3) and (4) are, respectively, the mutation operation and crossover operation in DE.

Although the model in this paper shares the same features (e.g., simulation-based, constrained, and multi-dimensional problem) with the TEAM workshop problem 22 and the loudspeaker model as in [17–19], this model requires substantially longer simulation time than

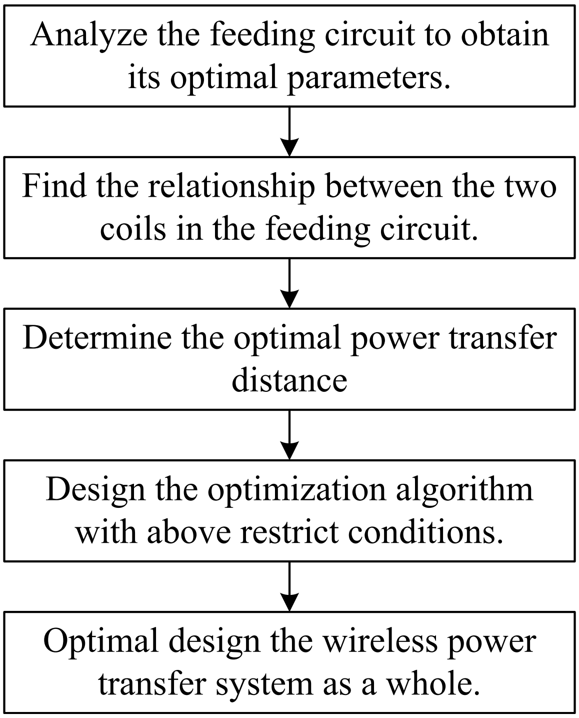
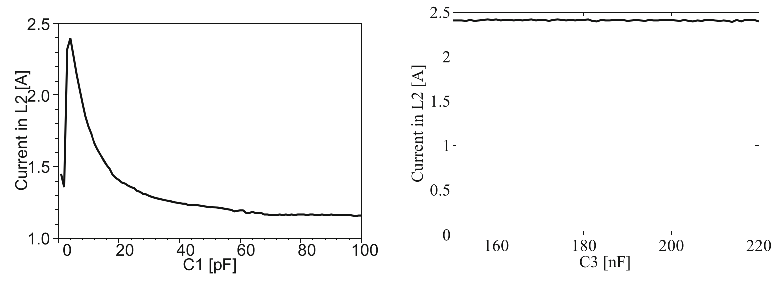


Fig. 4 The design flowchart of the WPT system



a

b

Fig. 5 Output current in L_2 varied with C_1 and C_3

previous models. Therefore, we propose to employ the following techniques for handling our problem.

1. DE algorithm is applied several times to tackle our problem. In the first trial, random initialization is used, while in the following trials, we embed the best found solution in previous trials into the initial population. In this way, DE starts in a good position in the subsequent trials.
2. Solution revisiting happens when a heuristic algorithm converges to global/local optima. In preventing revisiting and saving simulation time, we use a non-revisiting scheme [20]. This scheme stores all solutions in a binary space-partitioning tree structure. This scheme requires more computer memory than an algorithm without this scheme; however, saving simulation time is more important than memory consumption in our case.

With the above two techniques, we expect that a good solution can be found.

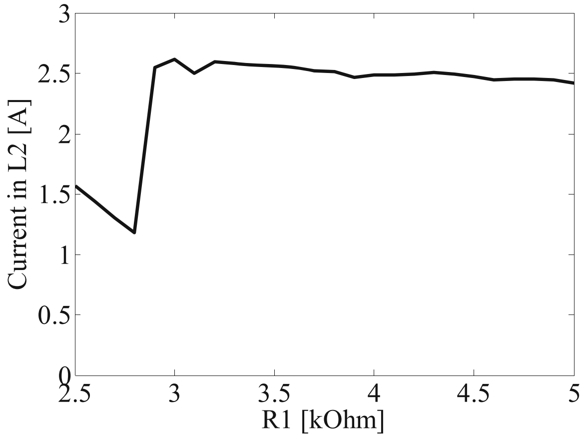


Fig. 6 Output current in L_2 varied with R_1

3.4 Three-coil wireless power transfer system with the feeding circuit and load circuit

According to the above description on the feeding circuit, the wireless power transfer can be analyzed as a three-coil system as shown in Fig. 8. The coils L_1 and L_2 are combined as the transmitter coil while the coil L_3 is the receiver coil. M is the mutual inductance between the two coils.

According to the electromagnetic theory, the strength of the magnetic field generated by the coil is proportional to its current which can be described as (4).

$$H(x,r)=\frac{I\cdot r^2}{2\sqrt{(r^2+x^2)^3}}, \tag{4}$$

where r is the radius of the circular coil. From the above equation, it can be seen that H can be maximized when $r=\sqrt{2}x$. Therefore, the outer diameter of the transmitter coil can be chosen from $D_{T_{out}}=2\sqrt{2}d$ where d is the power transfer distance.

In order to obtain a sensible design, the size of the receiver coil should be determined initially. In this research, it is assumed that the WPT system is designed for use in

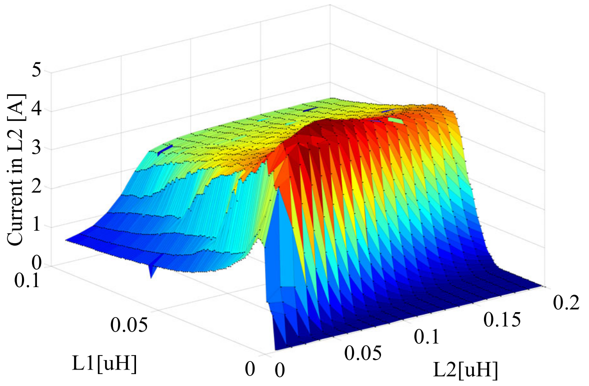


Fig. 7 Output current in L_2 varied with the values of L_1 and L_2

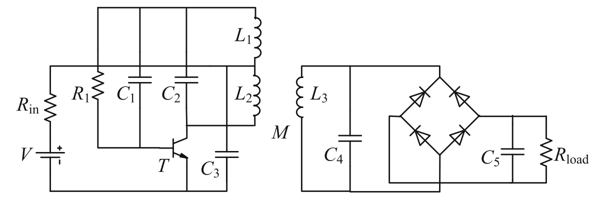


Fig. 8 WPT system with the feeding circuit and the load circuit

implanted medical devices. The size of the receiver coil, therefore, should be as small as possible. The frequency is chosen to be 13.56 MHz. Based on the above analysis, the WPT system as shown in Fig. 8 is optimized as an integrated system.

During the optimization, the optimization objective function is the power transfer efficiency which is expressed as:

$$\eta = \frac{P_{\text{Load}}}{P_{\text{Source}}} = \frac{I_{\text{Receiver}}^2 R_{\text{Load}}}{U_{\text{Source}} I_{\text{Transmitter}}} \tag{5}$$

$$\text{subject to } D_{T_{out}} = 2\sqrt{2}d \tag{6}$$

where P_{Load} and P_{Source} are the power in the load and the source respectively; I_{Receiver} and $I_{\text{Transmitter}}$ are the currents in the receiver coil and the transmitter coil. The relationship of the power transfer distance and the diameter of the transmitter coil are the constraint condition.

4 Results

In order to reduce the AC resistance of the wire, the Litz wire is used to construct the receiver coil and the transmitter coil is made of copper wire. Through analysis, the relationship between the power transfer efficiency and the number of strands and number of turns of the receiver coil is shown in Fig. 9.

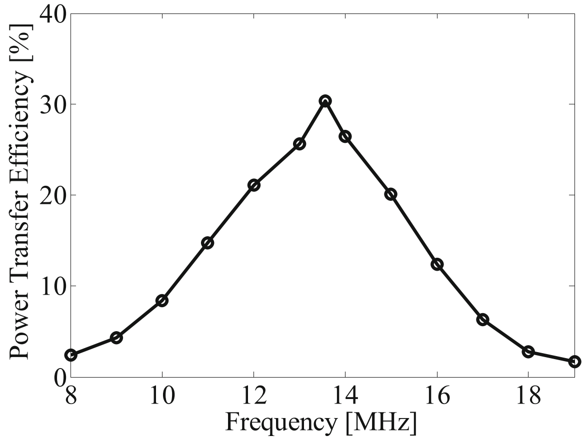


Fig. 9 Power transfer efficiency varied with frequency

Table 2 Specifications of the transmitter coil and the receiver coil

	Parameters		Values
Transmitter coil	Coil L_1	Number of turns	1
		Number of strands	4
		Diameter of coil	64 mm
		Diameter of wire	3 mm
	Coil L_2	Number of turns	2
		Diameter of coil	64 mm
		Diameter of wire	3 mm
		Number of strands	4
Receiver coil	Number of turns		5
	Diameter of coil		10 mm
	Diameter of wire		1 mm

After optimization design, the parameters of the transmitter coil and the receiver coil are listed in Table 2.

According to (1), the change of C_2 will determine the frequency of the output current in L_2. The optimal results in Table 2 are based on the 13.56 MHz. The power transfer efficiency curve varied with different frequencies through changes in the value of C_2 is shown in Fig. 9. The power transfer efficiency achieves the maximum value (about 30%) when the frequency is 13.56 MHz.

5 Conclusions

Wireless power transfer technology has a great application potential in implanted medical devices. Different from the previous research, in this paper, the optimization design for the WPT system not only includes the coil system but also considers the influence of the power source. In order to simplify the system, a simple feeding circuit is applied in the WPT system to convert a DC source into an AC source. The property of this feeding circuit is firstly analyzed, and the relationship between the parameters in the circuit is concluded in this paper. Then the optimization method is applied to optimize and design the WPT system as a whole. The results indicate that this method can obtain the optimal performance of the WPT system.

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Competing interests

The authors declare that they have no competing interests.

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References

1. N Tesla, The transmission of electrical energy without wires as a means for furthering peace. Electrical World and Engineer **1**, 21–21 (1905)

2. SYR Hui, W Zhong, CK Lee, A critical review of recent progress in mid-range wireless power transfer. IEEE Trans. Power Electronic **29**(9), 4500–4511 (2014)
3. W Brown, The history of power transmission by radio waves. IEEE Transactions on Microwave Theory and Techniques **32**(9), 1230–1242 (1984)
4. AK RamRakhyani, S Mirabbasi, M Chiao, Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants. IEEE Transactions on Biomedical Circuits and Systems **5**(1), 48–63 (2011)
5. Z Yang, W Liu, E Basham, Inductor modeling in wireless links for implantable electronics. IEEE Transactions on Magnetics **43**(10), 3851–3860 (2007)
6. Q Xu, H Wang, Z Gao, Z Mao, J He, M Sun, A novel mat-based system for position-varying wireless power transfer to biomedical implants. IEEE Transactions on Magnetics **49**(8), 4774–4779 (2013)
7. C Liu, Y Guo, H Sun, S Xiao, Design and safety considerations of an implantable rectenna for far-field wireless power transfer. IEEE Transactions on Antennas and Propagation **62**(11), 5798–5806 (2014)
8. A Kurs, A Karalis, R Moffatt, JD Joannopoulos, P Fisher, M Soljacic, Wireless power transfer via strongly coupled magnetic resonances. Science **317**(5834), 83–86 (2007)
9. A Karalis, JD Joannopoulos, M Soljacic, Efficient wireless non-radiative mid-range energy transfer. Annals of Physics **323**, 34–48 (2008)
10. Z Xiu, HL Li, SL Ho, WN Fu, A hybrid optimal design strategy of wireless magnetic-resonant charger for deep brain stimulation devices. IEEE Trans. Magn. **49**(5), 2145–2148 (2013)
11. SR Khan, GS Choi, Optimization of planar strongly coupled wireless power transfer system for biomedical applications. Microwave and Optical Technology Letters **58**(8), 1861–1866 (2016)
12. Z Xiu, SL Ho, WN Fu, Analysis and optimization of magnetically coupled resonators for wireless power transfer. IEEE Trans. Magn. **48**(11), 4511–4513 (2012)
13. S Barmada, M Raugi, M Tucci, A multi-objective optimization algorithm based on self-organizing maps applied to wireless power transfer systems. International Journal of Numerical Modelling: Electronic Networks Devices & Fields (2016)
14. Z Wu, X Xia, B Wang, Improving building energy efficiency by multiobjective neighborhood field optimization. Energy and Buildings **87**, 45–56 (2014)
15. Z Wu, TWS Chow, Binary neighbourhood field optimization for unit commitment problems. IET Generation, Transmission & Distribution **7**(3), 298–308 (2013)
16. [online available] http://skory.gylcomp.hu/kapcs/kapcs.html. Accessed 1 Feb 2017.
17. JP Cukovic, B Klopcic, M Petrun, B Polajzer, D Dolinar, Optimization of resistance spot welding transformer windings using analytical successive approximation and differential evolution. IEEE Transactions on Magnetics **50**(4), 1–4 (2014)
18. X Zhang, Z Xin, SL Ho, WN Fu, Designing loudspeaker by ensemble of composite differential evolution ingredients. IEEE Transactions on Magnetics **50**(11), 1–4 (2014)
19. GC Tenaglia, L Lebensztajn, A multiobjective approach of differential evolution optimization applied to electromagnetic problems. IEEE Transactions on Magnetics **50**(2), 625–628 (2014)
20. SY Yuen, CK Chow, A genetic algorithm that adaptively mutates and never revisits. IEEE Transactions on Evolutionary Computation **13**(2), 454–472 (2009)

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